Heat Flux Measurements for Supersonic Film Cooling

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Outline

- **Background**
- **Previous Work**
- **Objectives**
- **Methodology**
- **Results**
- **Next Steps**

Film Cooling

- What is Film Cooling?
  - Thermal protection technique where a cooler gas injected along a critical surface creates an insulating layer that protects it from hot combustion products.
- Applications
  - Gas Turbines
    - Combustor liner
    - Turbine blades
  - Rockets
    - Nozzle extension

Gas turbine combustor

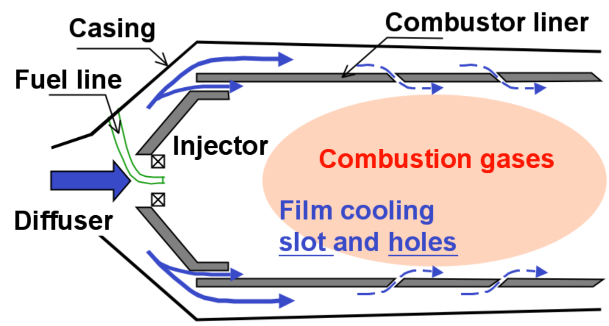
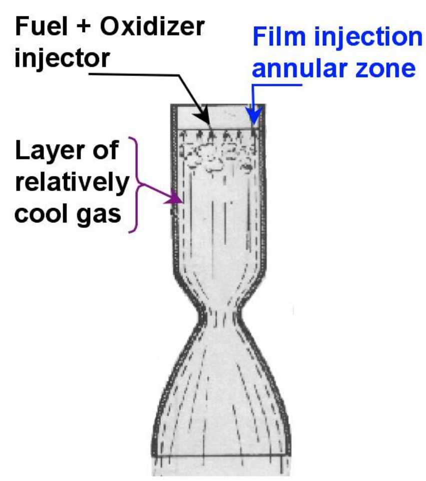


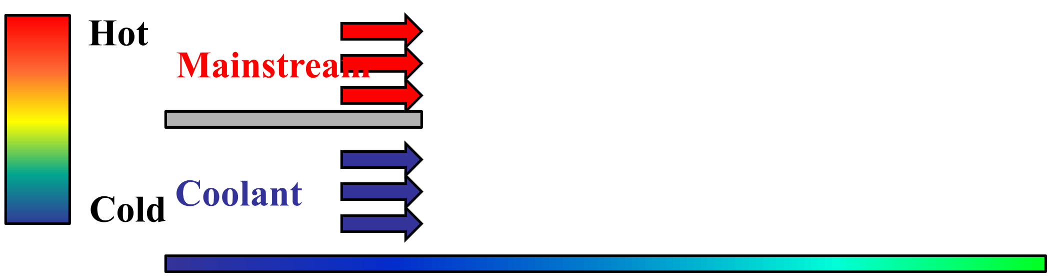
Figure Adapted from Cruz (2008)

Rocket thrust chamber or Nozzle Extension



Adapted from (Sutton, 1986)

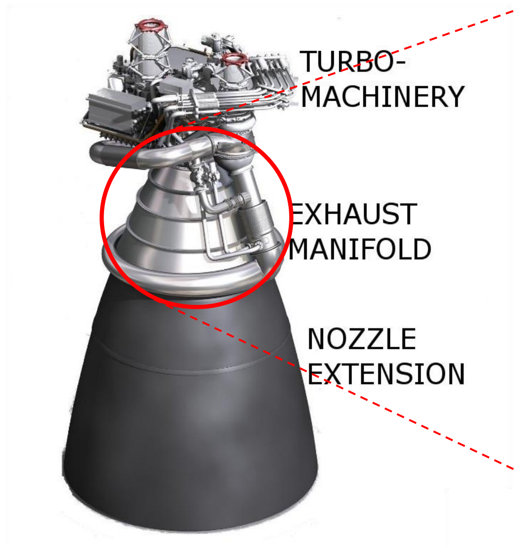
J-2X Concept

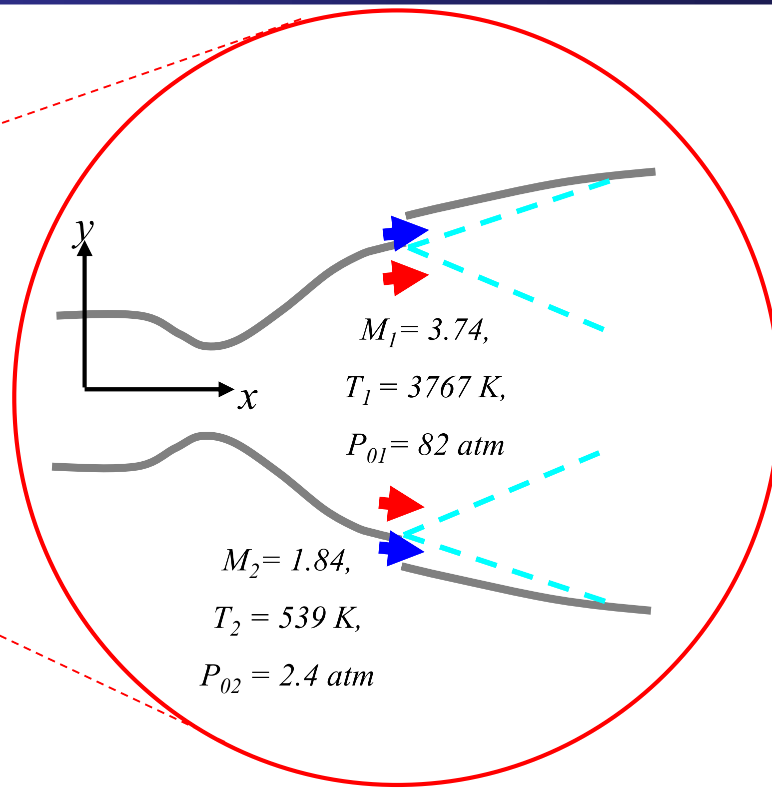


Film Cooled Wall

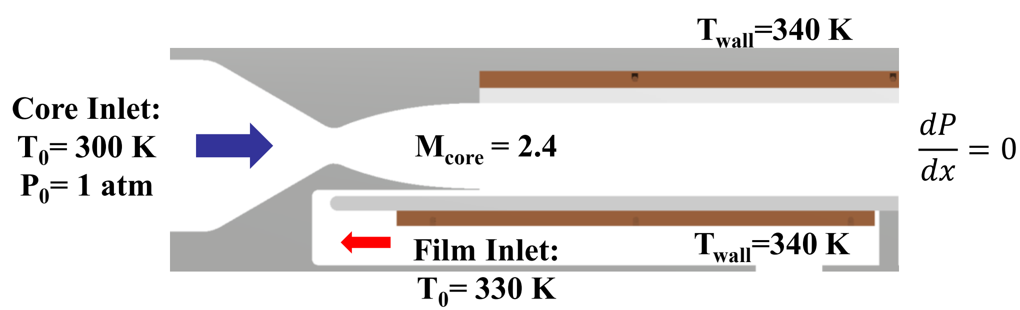
J-2X Comparison

- J-2X nozzle extension

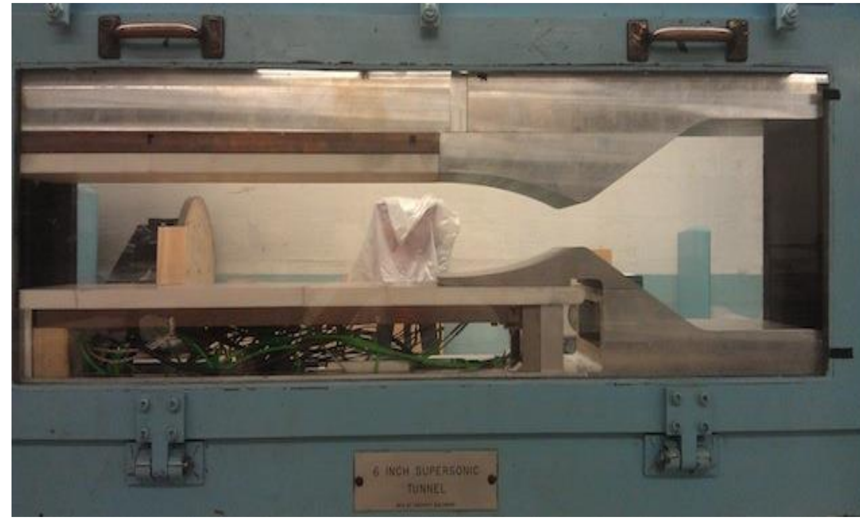




- UMD tunnel
  - J-2X analogue
  - Various film flow cases:
    - Case 0 – no film
    - Case 1 – $M_{film} = 0.5$
    - Case 2 – $M_{film} = 0.7$
    - Case 3 – $M_{film} = 1.2$



UMD Supersonic Wind Tunnel



- Basic Specs
  - Transient facility (6-10 sec run time)
  - Working fluid: Air
  - Total P, T: Ambient
  - Test section Dimension: 12”x6”x26”
- The tunnel cannot directly match J-2X conditions so special care must be taken to design analagous experiments.
  - Heat walls to ensure that the heat flux vector always points into the flow
  - Heat film to ensure temperature “cascade” is preserved

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Literature Review

- Experiments, Scaling Laws, and Simulations
  - **Wieghardt (1946)** – Established much of the scaling regarding film cooling. Actually analyzed film heating and found similarity relationship for downstream thermal profiles, as well as a model for the wall effectiveness scaling.
  - **Lucas and Golladay (1963)** – Studied film cooling in a rocket nozzle in the presence of accelerating flow, measuring mass flow rates, wall temperatures and wall pressures
  - **Goldstein (1971)** – Comprehensive review of film cooling scaling laws. Most analysis uses a fully developed turbulent boundary layer and features scaling using the blowing ratio and slot height
  - **Aupoix et al. (1998)** – Performed one of the seminal supersonic film cooling studies by exploring the mixing of a supersonic film with a supersonic mainstream for overexpanded, under-expanded and perfectly expanded films. Total pressure, static temperature and total temperature probes were used to extract profiles at different downstream stations. Wall pressures and adiabatic wall temperatures are also provided. Additionally several different RANS turbulence models were tested using a boundary layer code. Boundary layer code was noted to be incapable of capturing the initial mixing but downstream mixing trends were captured adequately.
  - **Konopka et al. (2010)** – Performed the first supersonic LES of film cooling and compared simulation wall temperatures with experimental data and found excellent agreeement.
- More experimental data are needed for validating supersonic film cooling CFD
  - Most studies do not provide flow profiles or turbulence intensity info.
  - No studies provide minimally-intrusive flow profiles.
- More work is required to assess suitability of RANS and LES approaches for film cooling flows.

Literature Review, Cont

- Work At UMD
  - **Cruz (2008)** – Adiabatic and non-adiabatic film cooling experiments for multiple blowing ratios (BR=0.6, 1.2, 3.0) using microthermocouples, PIV and IR thermography. Provided mean velocity and temperature profiles turbulent kinematic and thermal profiles, wall heat transfer, adiabatic wall effectiveness and skin friction at several downstream locations. Had uncontrolled flow conditions affecting film cooling mixing. Performed incompressible LES calculation of adiabatic wall jet case.
  - **Dellimore (2010)** – Modified Simon's incompressible model for slot film cooling to account for compressibility effects and mainstream pressure gradients. Used RANS techniques to simulate supersonic film cooling experiments of Maqbool (2011) in addition to the experiments of Cruz (2008).
  - **Maqbool (2011)** – Performed supersonic film cooling experiments for both subsonic and supersonic films; developed an efficient wall heat transfer technique that calculates the heat flux at the wall based on internal embedded thermocouples; most of the film cooling experiments were performed with film total pressures equal to the mainstream; used Schlieren to capture shock structures. Captured wall pressures and wall temperatures as well
  - **Voegele (2011 & 2013)** – Presented RANS simulations of 2D adiabatic, slot film cooling of adiabatic experiments. Used a variety of inflow specification techniques to test RANS performance. Also explored turbulence models and effect of turbulent Prandtl number. Found the kinematics were captured well but the thermal fields were not captured very well. Also captured adiabatic and non-adiabatic film cooling experiments. Used variable-density LES to accurately capture subsonic film cooling performance in terms of both flow profiles and wall heat transfer characteristics.

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Objective

Improve experimental apparatus and acquire more and better data

- Correct problem with previous nozzle
- Acquire more/better heat flux data
- Acquire higher quality Schlieren images over the entire test section
- Improve our understanding of the heat flux measurement technique
  - Reduce measurement uncertainty

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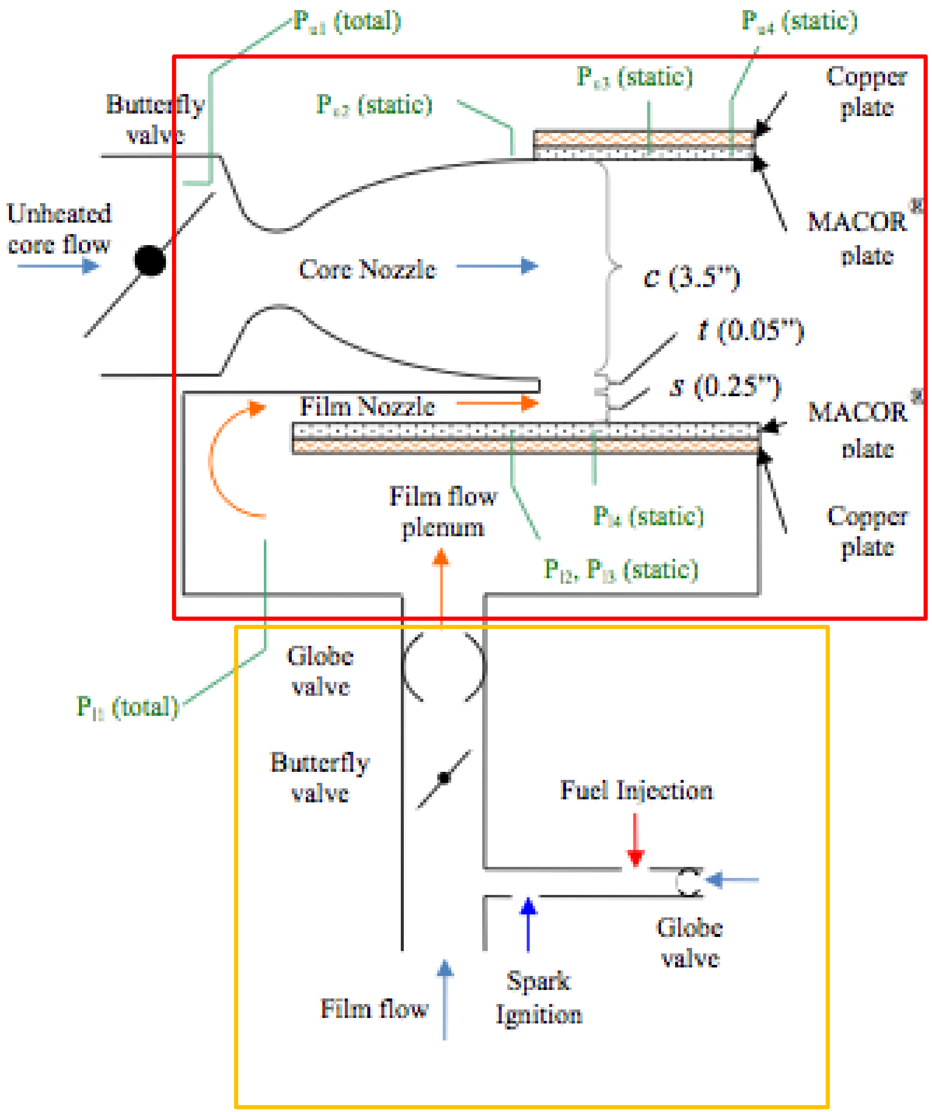
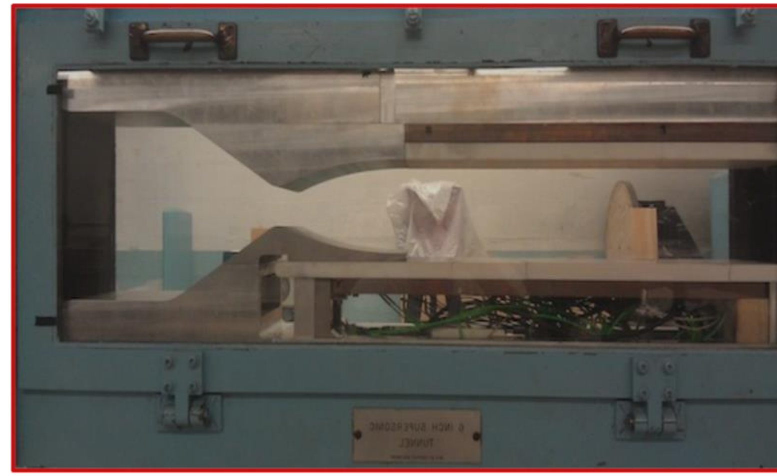
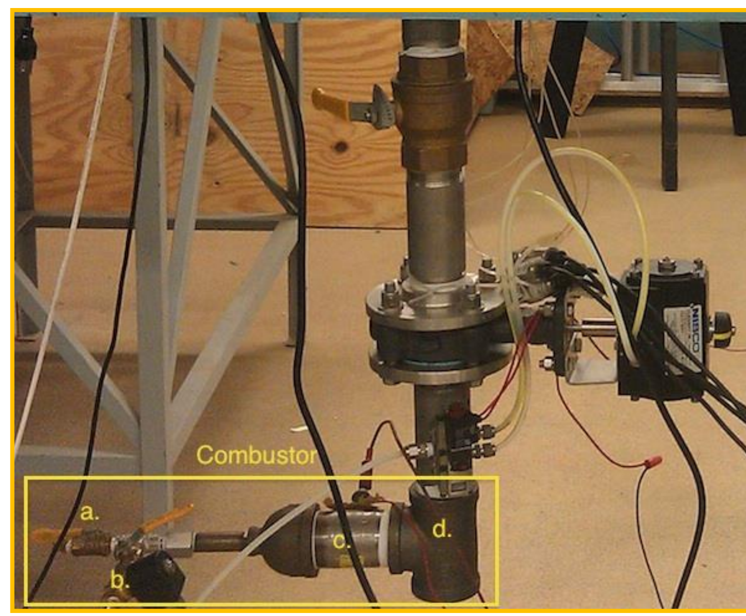
Experiment Overview



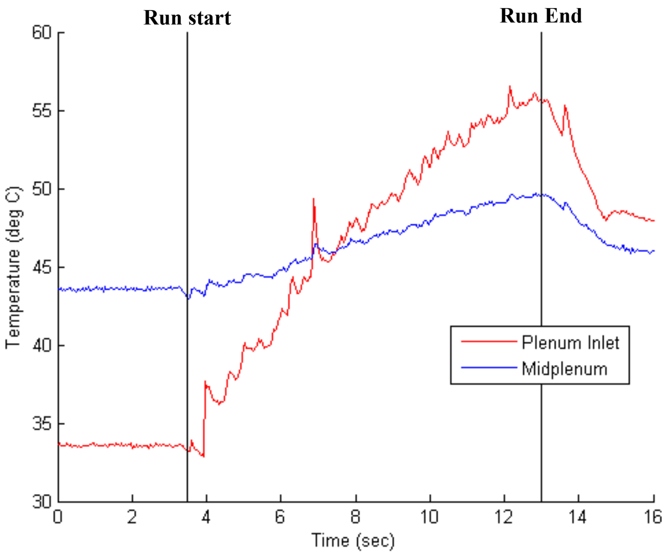




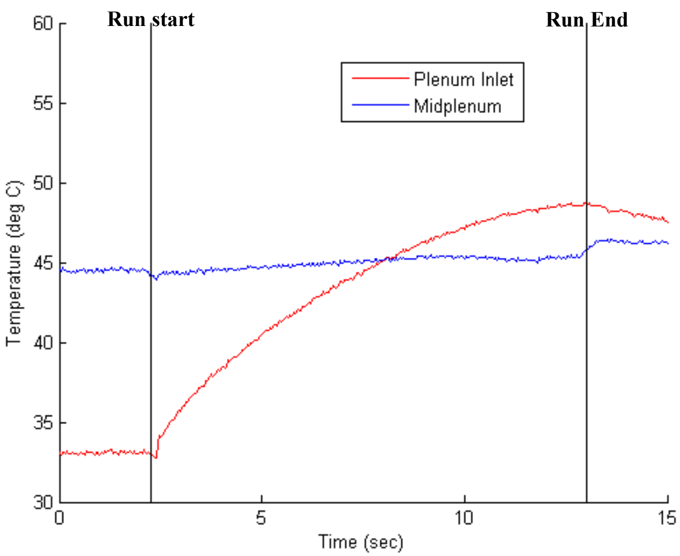
Film Heating Methods

- Initial film heating method: Propane burner
  - Difficult to tune, produced very transient results, added an order of complexity to the system
- Heat gun development
  - Simple substitution of an electric heat gun for the combuster
  - The heat gun was found to produce more stable heating with much simpler operation

- **Propane Burner (Case 3)**



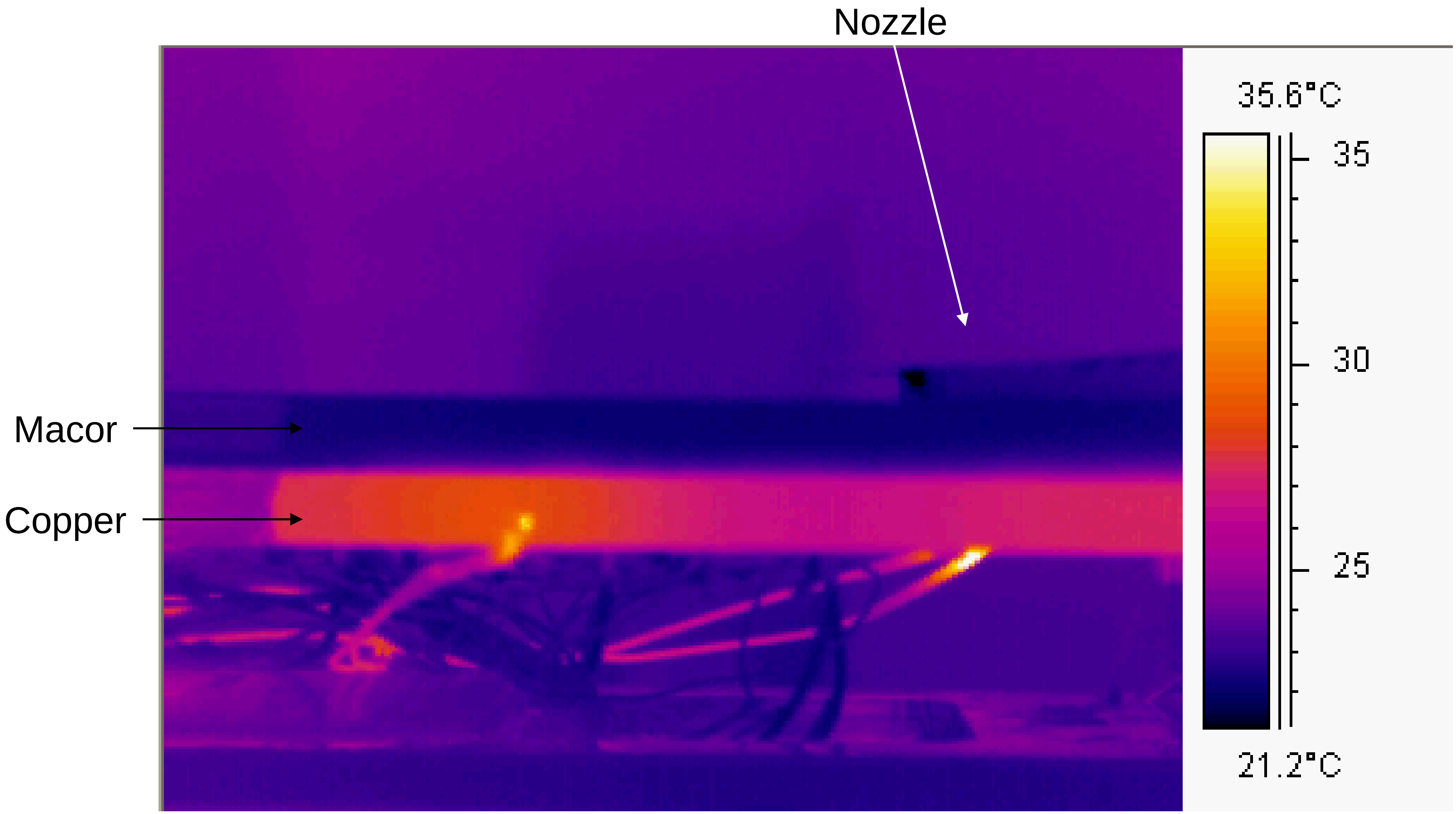
- **Heat Gun (Case 2)**



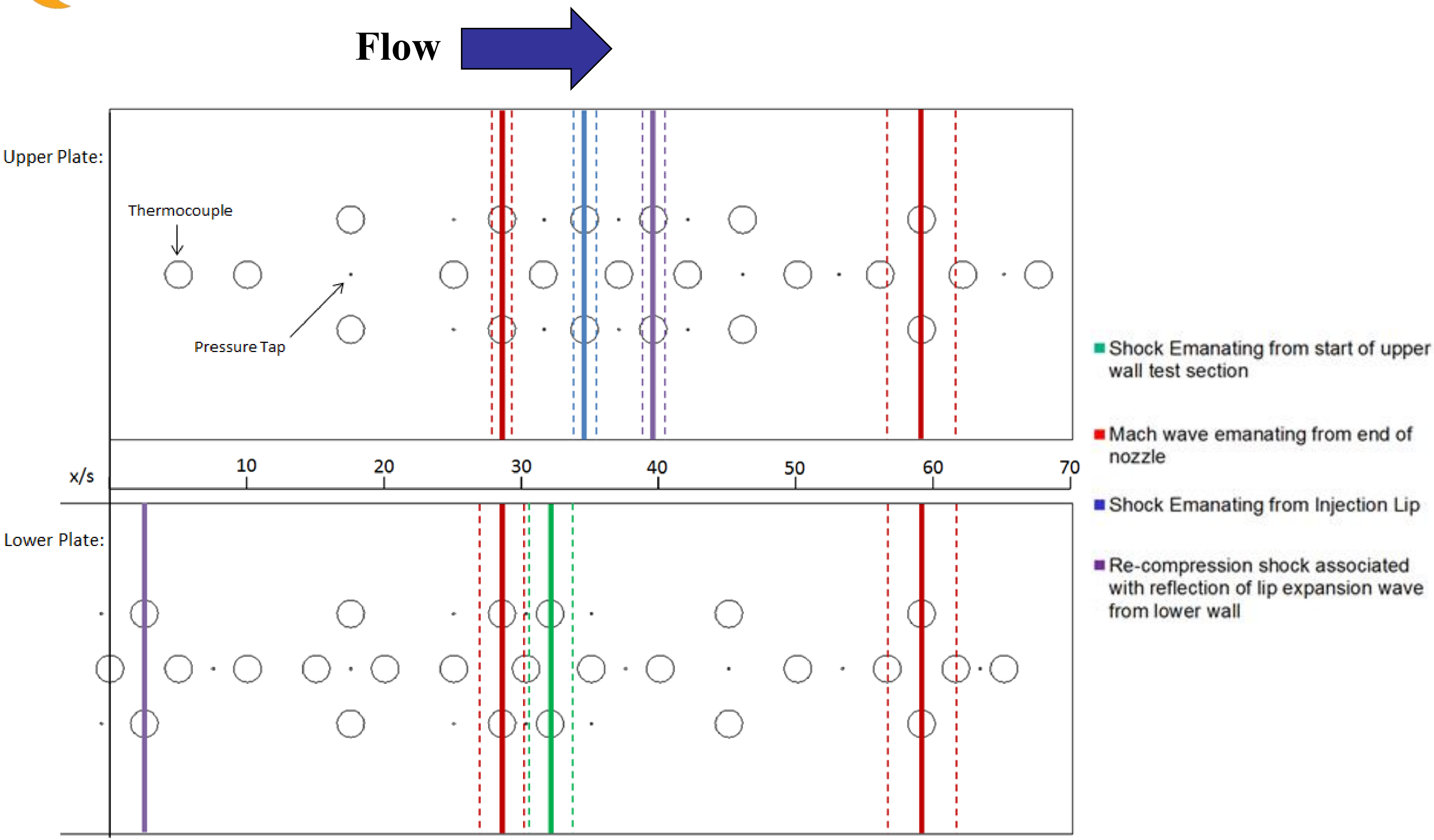
Operational Procedure

- Heat tunnel walls from ambient to 50 K above ambient (25-30 min)
- Pump down vacuum tanks to minimum pressure (15 min)
- Allow wall temperature to fall to ~43K above ambient and become isothermal (5-10 min)
- Start film heater
- Open butterfly valves to begin run
  - Collect pressure and temperature data
- Once flow becomes unsteady, close valves
- Begin reheating walls (10-15 min)
  - Typically, walls only fall 6-7K per run, so heating is faster after the first heat cycle

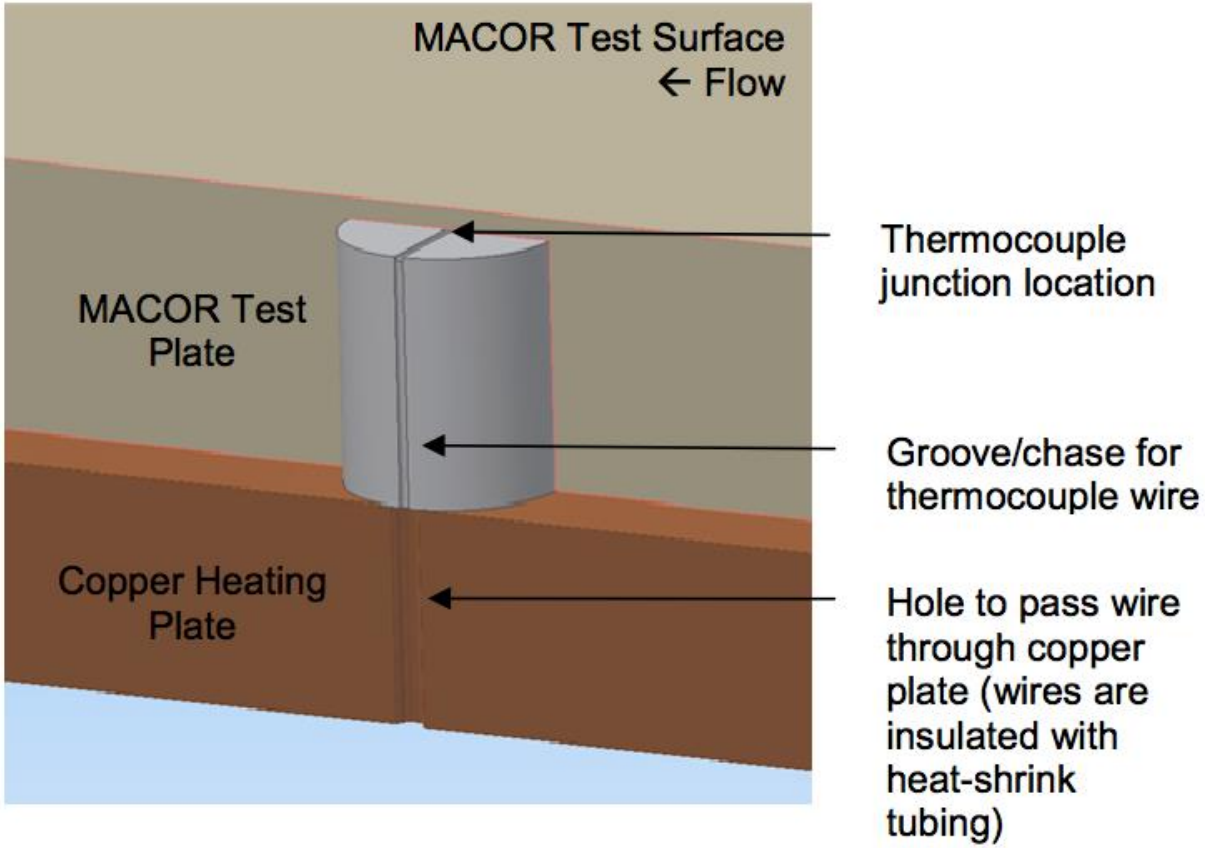
Lower Wall Infrared Measurement



Measurement and Shock Locations



Heat Flux Gauges



- Infer wall heat flux from sub-surface temperature-time histories
  - Inverse method
- Advantage: no disturbance to flow
- Disadvantage: complex data interpretation process

Heat Flux Measurements

- Governing Equation:

$$\boxed{\rho u\frac{\partial h_o}{\partial x}+\rho v\frac{\partial h_o}{\partial y}-\frac{\partial}{\partial y}\left(\frac{k}{c_p}\frac{\partial h_o}{\partial y}\right)=\frac{\partial}{\partial y}\left[\left(1-\frac{1}{\Pr}\right)\mu\frac{\partial(u^2/2)}{\partial y}\right]}$$

$$h_o=c_pT+\frac{u^2}{2}=c_pT_0$$

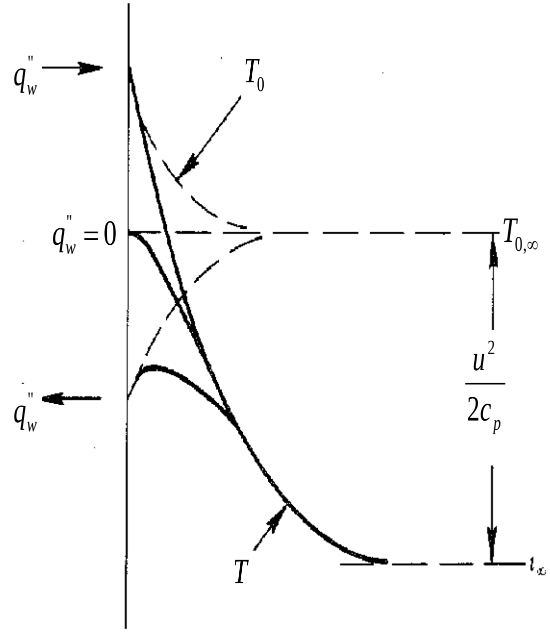
- Boundary Conditions (Pr=1):

$$\begin{array}{lll} u,v=0 & T_0=T_w & y=0 \\ u\to u_\infty & T_0\to T_{0,\infty} & y\to\infty \\ u=u_\infty & T_0=T_{0,\infty} & x=0 \end{array}$$

- Wall Heat Flux:

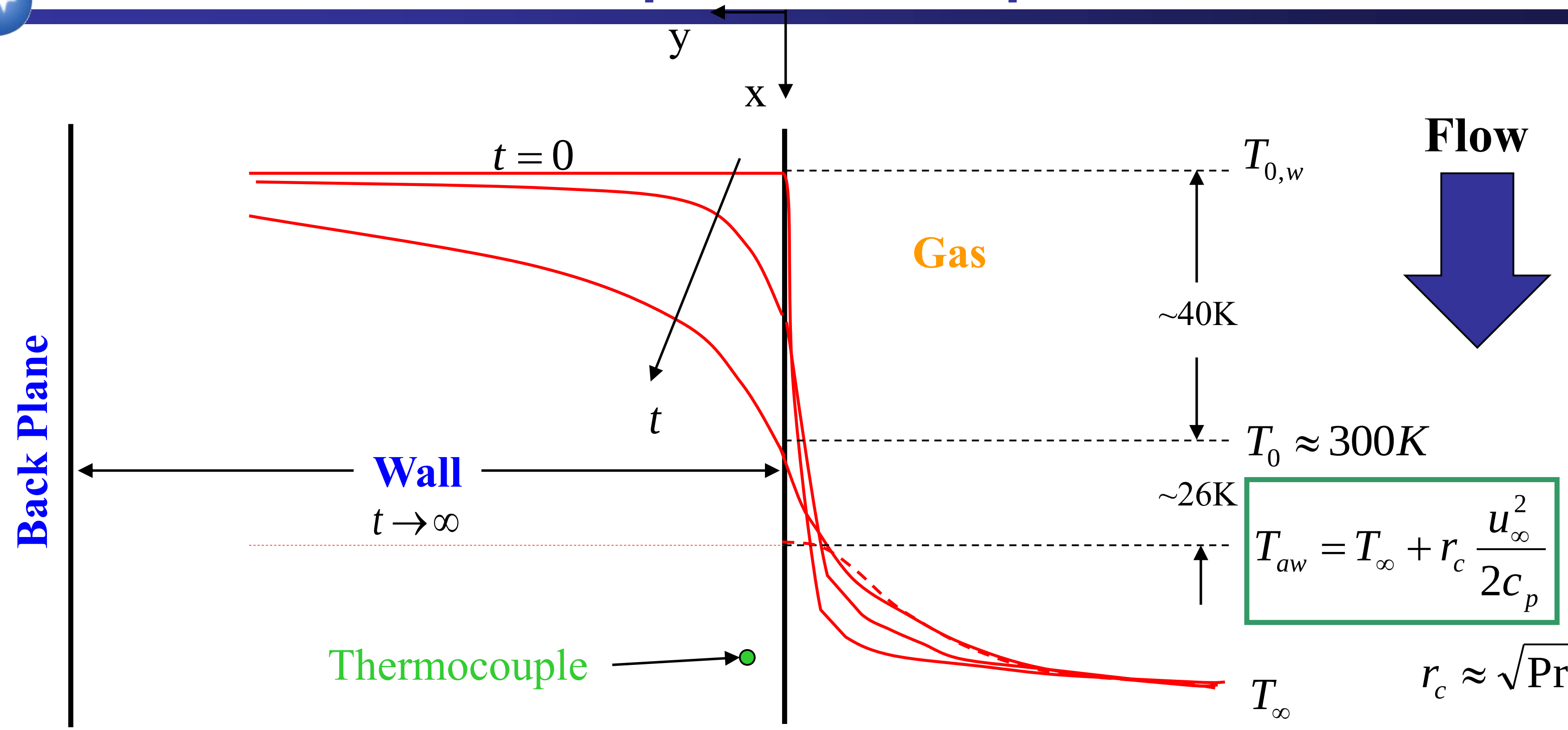
$$q_w''=-k\left(\frac{\partial T_0}{\partial y}\right)_w=h\left(T_w-T_{0,\infty}\right)$$

- Problem: In our expt., total T of air is same as T wall.
  - *Won't measure any heat flux w/o wall heating or cooling.*
  - We will heat the wall to ensure unidirectional heat transfer.



Ref: Kays & Crawford

Wall Temperature Response



Wall temperature response

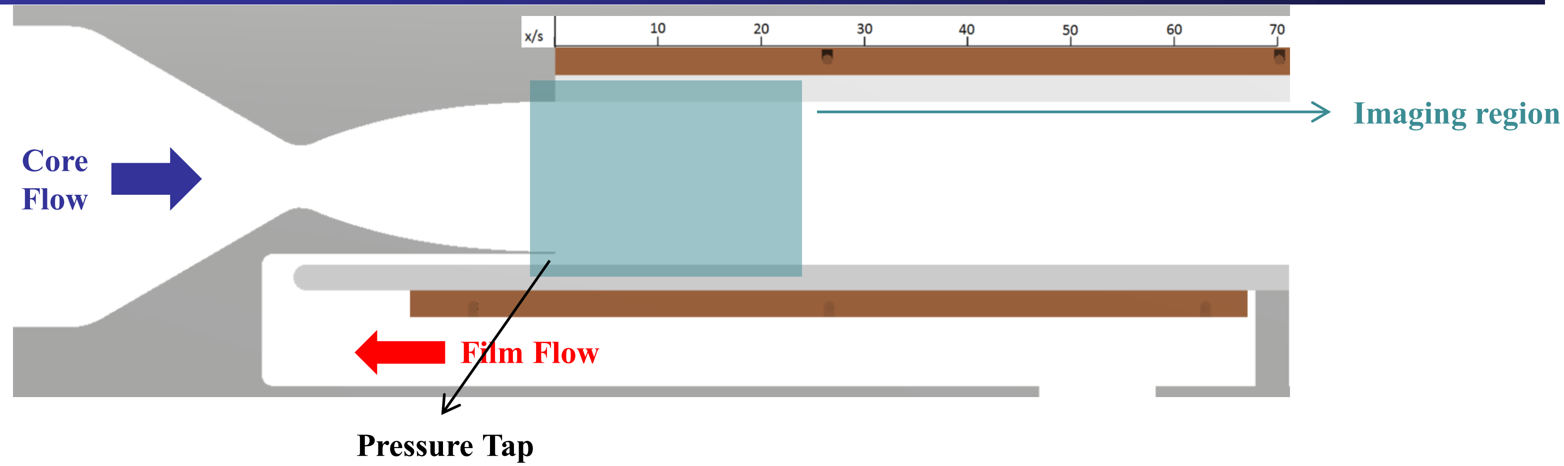
$$\frac{T - T_{0,w}}{T_{aw} - T_{0,w}} = erfc\left(\frac{y}{\sqrt{4\alpha t}}\right) - e^{\frac{hy}{k} + \left(\frac{h}{k}\right)^2 \alpha t} erfc\left(\frac{y}{\sqrt{4\alpha t}} + \frac{h}{k}\sqrt{\alpha t}\right)$$

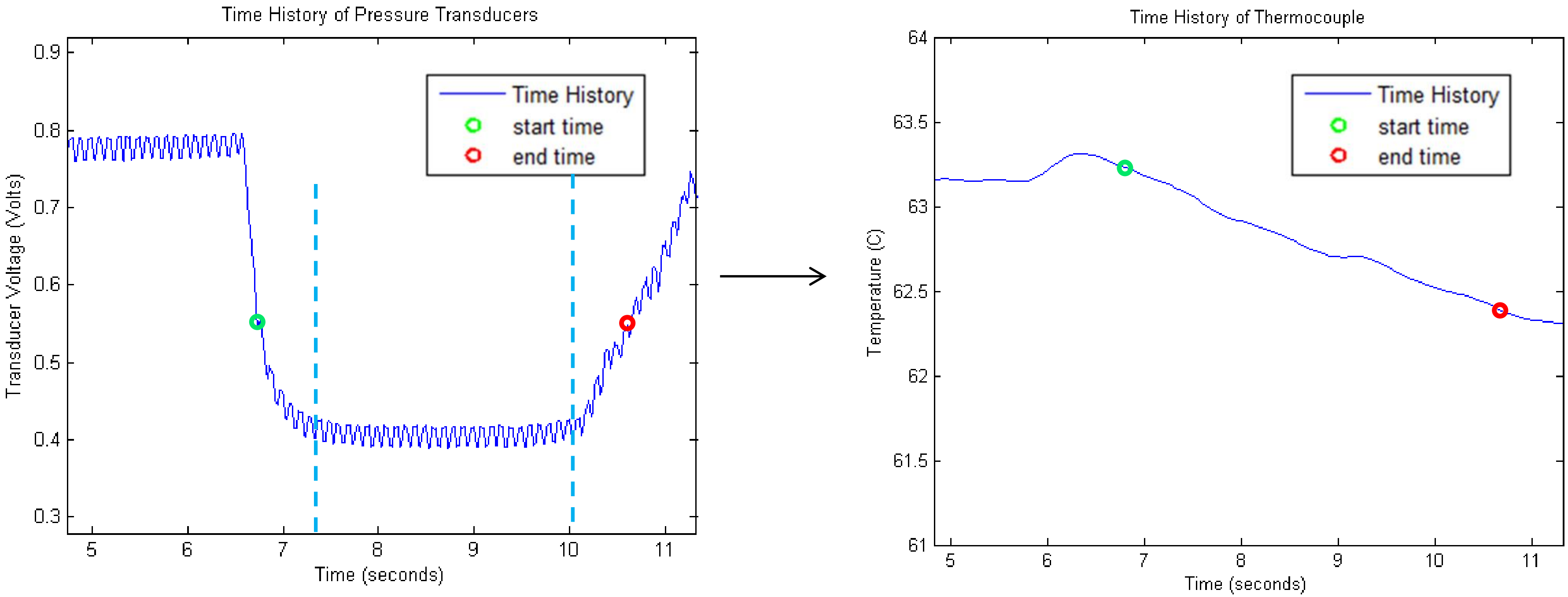
Heat flux

$$q_w'' = h\left(T_w - T_{aw}\right)$$

- $T_{backplane}$ must remain constant for wall T response equation to be valid
- Heat film to intermediate temperature to keep heat flux vector aligned
- Objective: extract heat flux from temperature-time histories

Data Acquisition Timing





Heat Flux Measurements: Curve Fitting

- Heat flux curve fit
  - Accomplished by solving the unsteady heat equation: $\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$

  with the following form suggested by Chen and Chiou:

$$f(\tau) = \sum_{n=1}^{N} b_n (4\tau)^n \Gamma(n+1) i^{2n} erfc\left(\frac{1}{2\sqrt{\tau}}\right)$$

Where b_n is determined by the curve fitting routine

  - Determine nondimensional surface temperature and heat flux via:

$$\theta(0,\tau) = \sum_{n=1}^{N} b_n \tau^n$$

and

$$-\frac{\partial \theta(0,\tau)}{\partial X} = \sum_{n=1}^{N} b_n \tau^{n-1/2} \frac{\Gamma(n+1)}{\Gamma(n+1/2)}$$

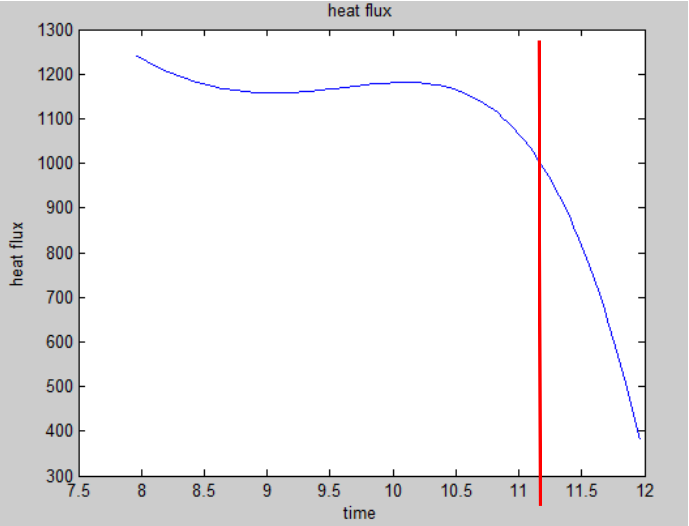
  - Return surface temperature and heat flux to dimensional values via:

$$T_s = T_0(1+\theta(0,\tau))$$

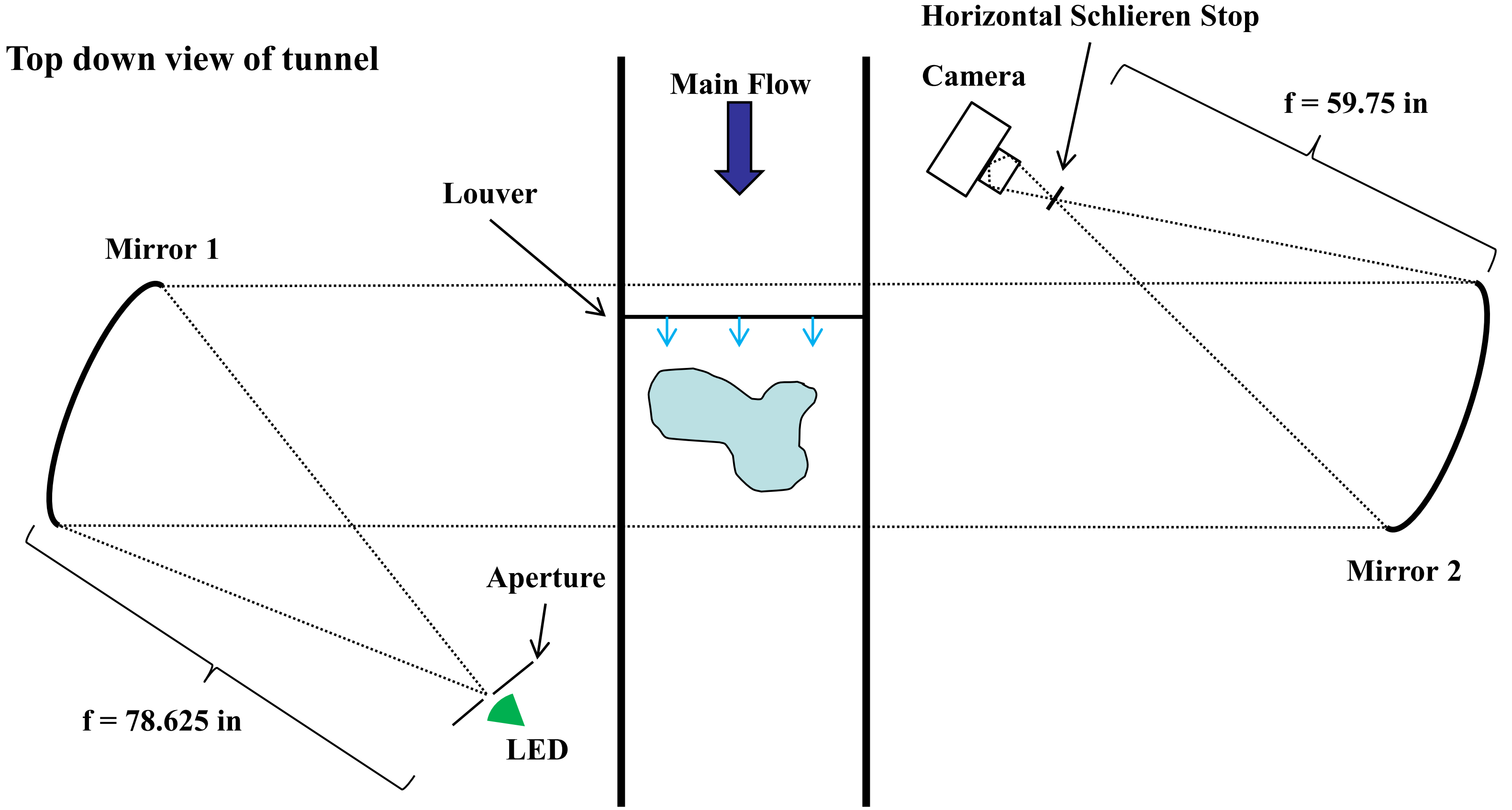
and

$$q = -\frac{kT_0}{x_1}\frac{\partial \theta(0,\tau)}{\partial X}$$

  - Heat flux fit produces variations at the end of the run, which are trimmed in accordance with the pressure based run definition as mentioned in the previous slide.



Schlieren System



- Z configuration
- Nikon D-90 with Nikon 70-300mm f/4-5.6G lens

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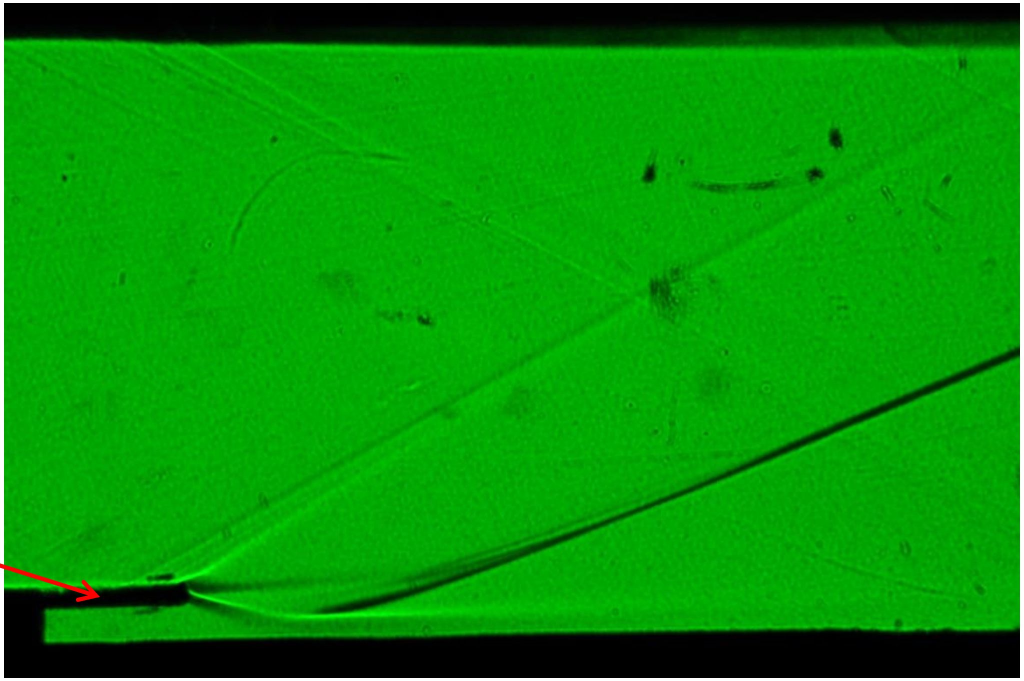
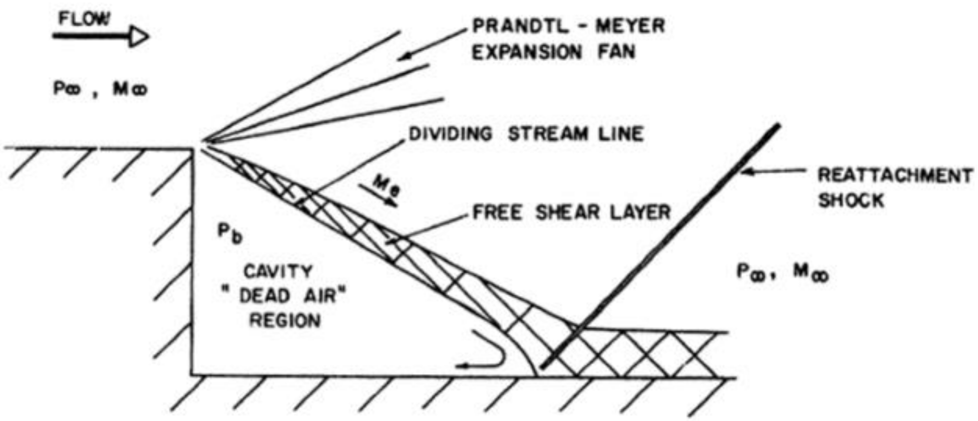
Flow Structure: Case 0 ($M_{film} = 0$)

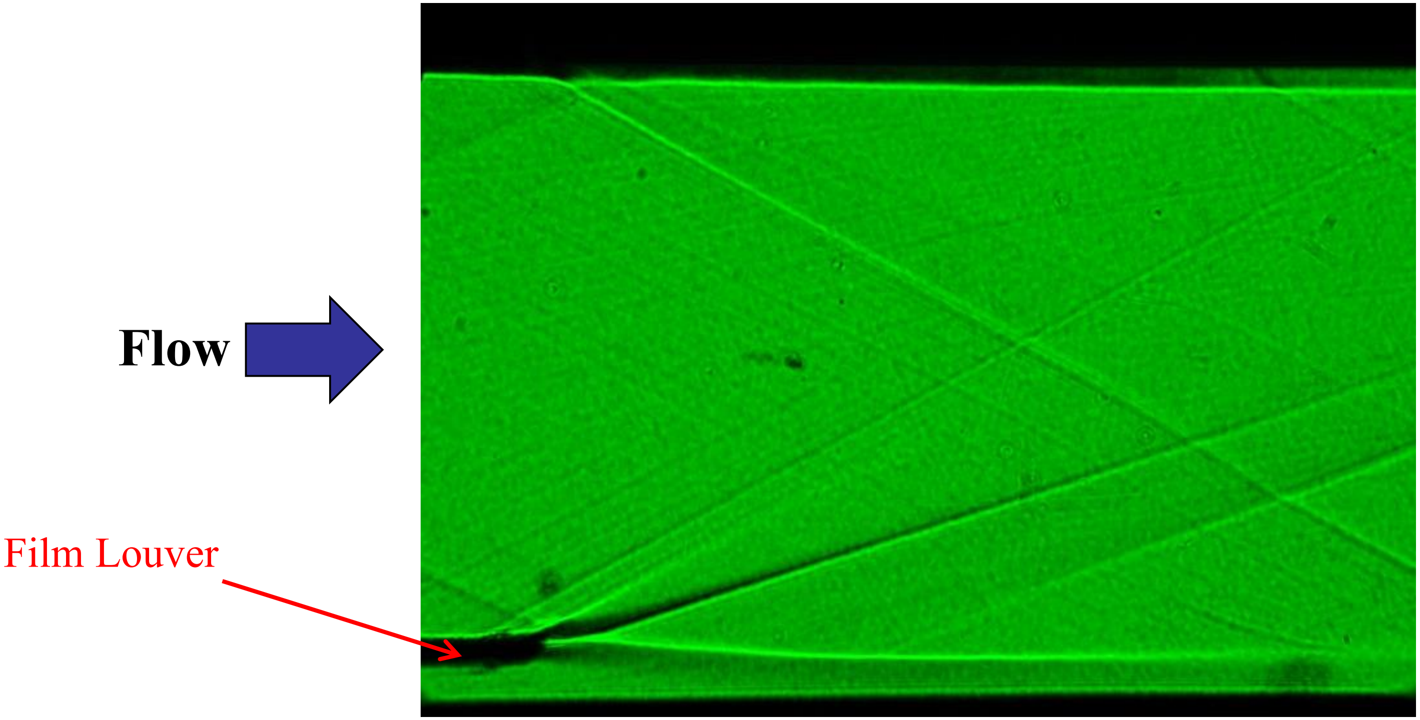
Flow

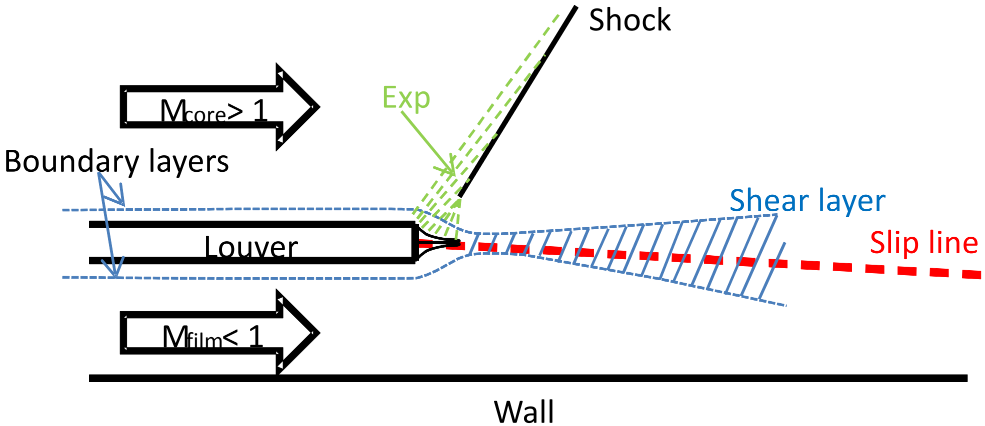
Film Louver





Flow Structure: Case 1 ($M_{film} = 0.5$)

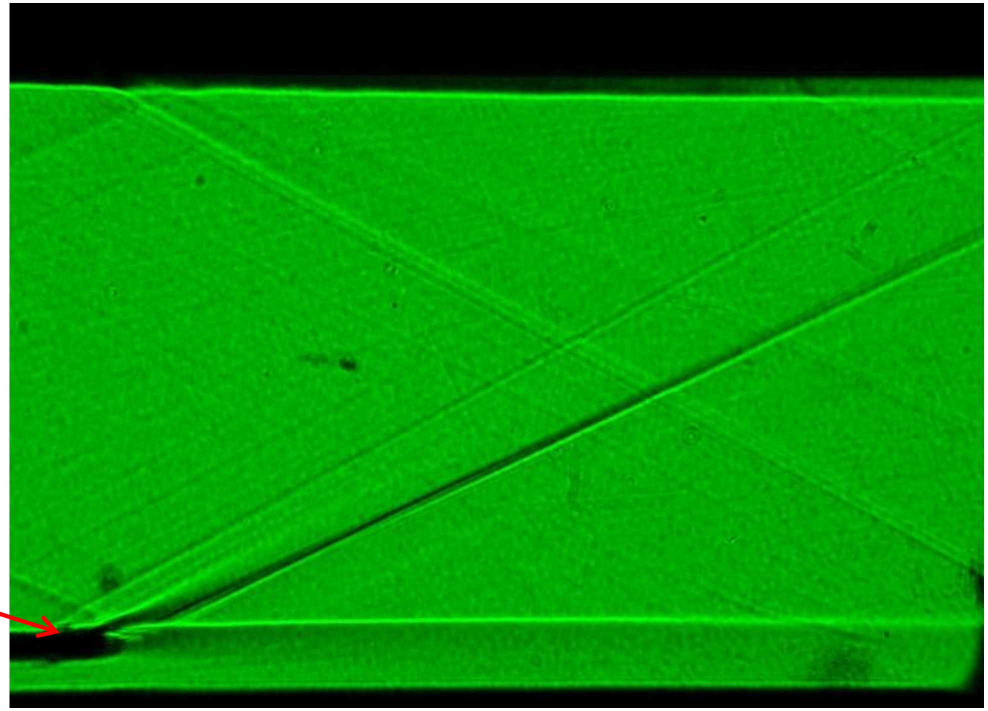


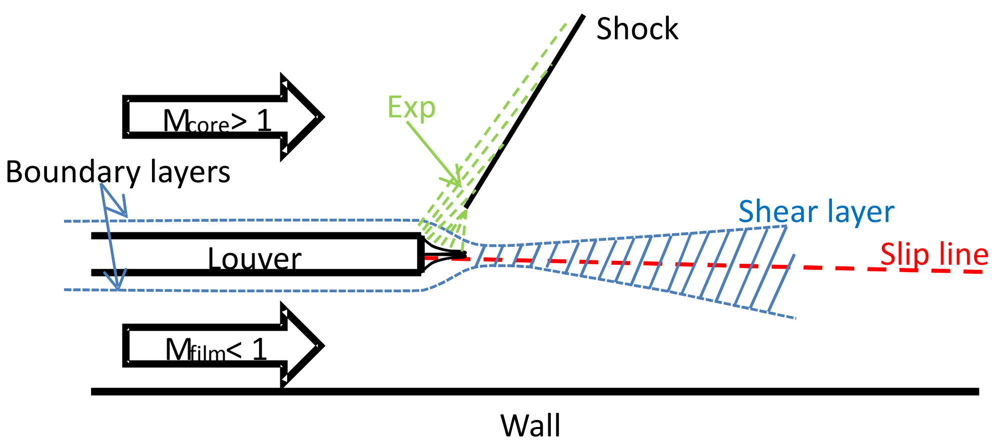


Flow Structure: Case 2 (M_{film} = 0.7)

Flow

Film Louver

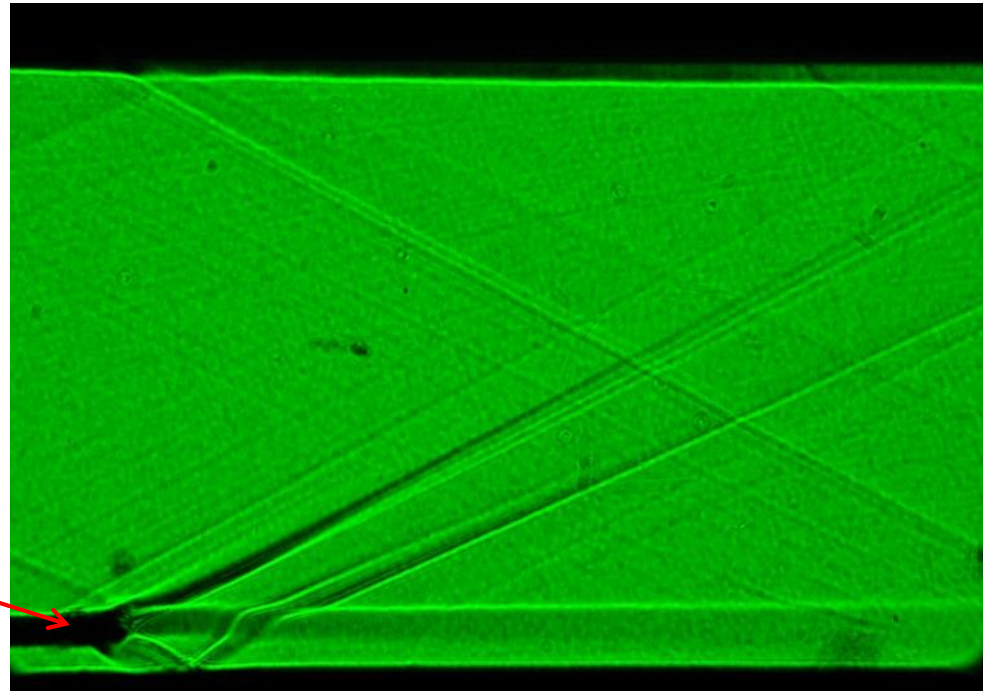


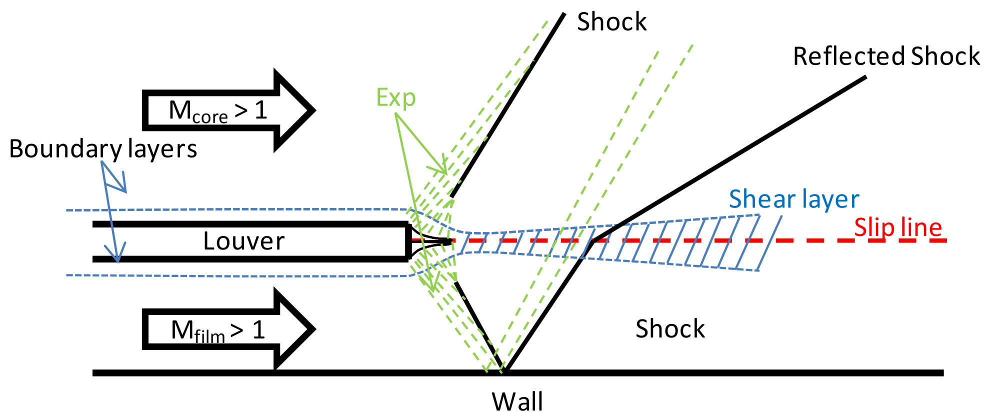


Flow Structure: Case 3 ($M_{film} = 1.2$)

Flow

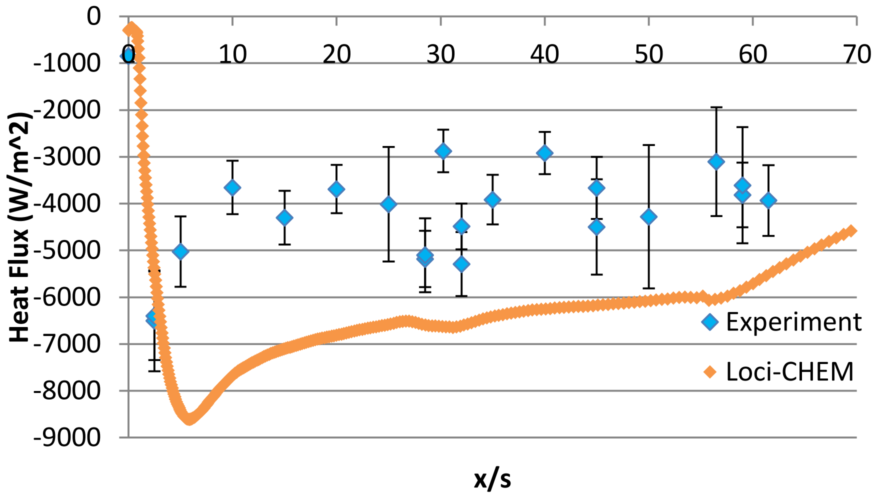
Film Louver



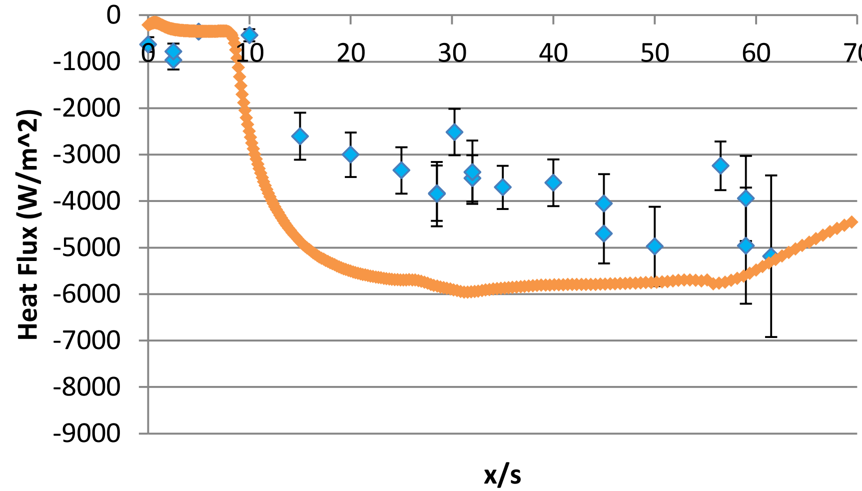


Heat Flux: Lower Wall

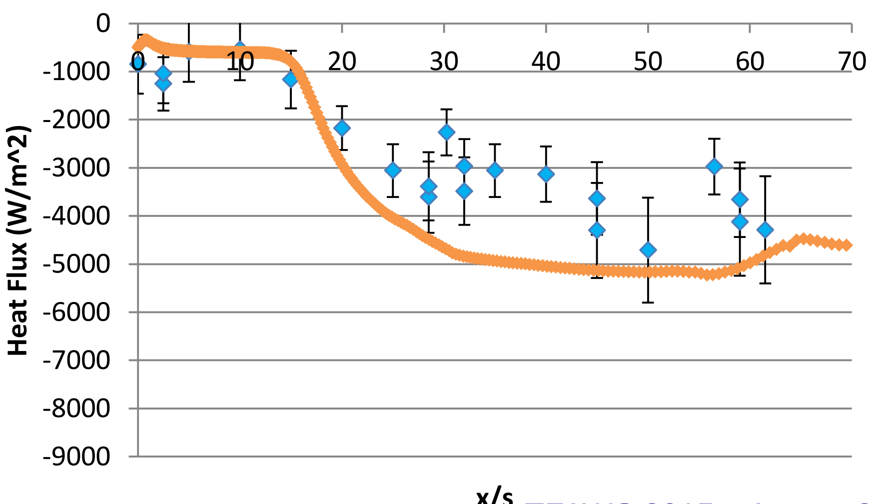
Case 0: Film Closed



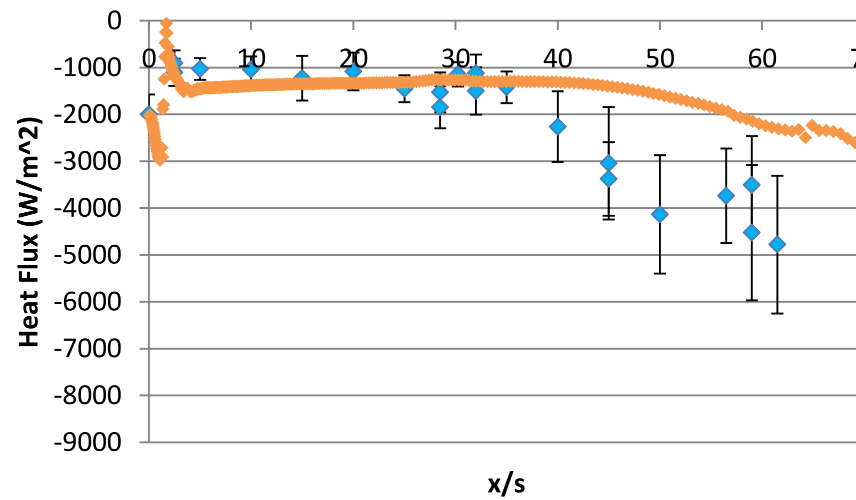
Case 1: Subsonic, M_{film} = 0.5



Case 2: Pressure Matched, M_{film} = 0.7



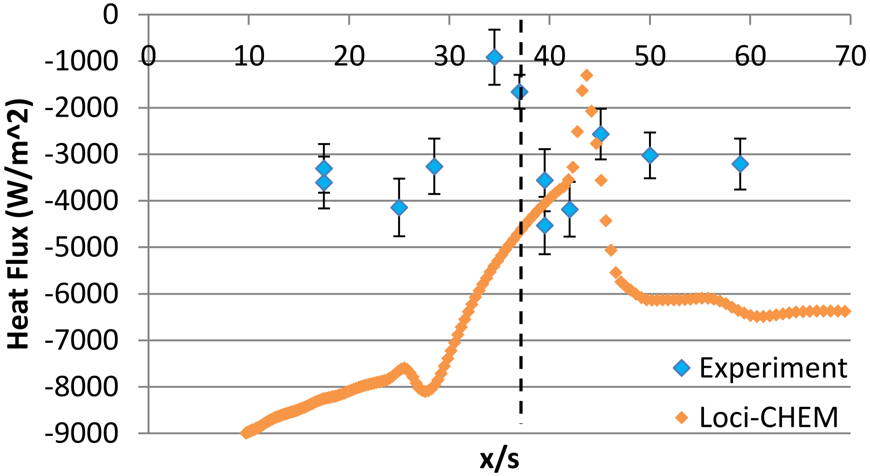
Case 3: Supersonic, M_{film} = 1.2



Heat Flux: Upper Wall

Lip Shock Impingement Location

Case 0: Film Closed



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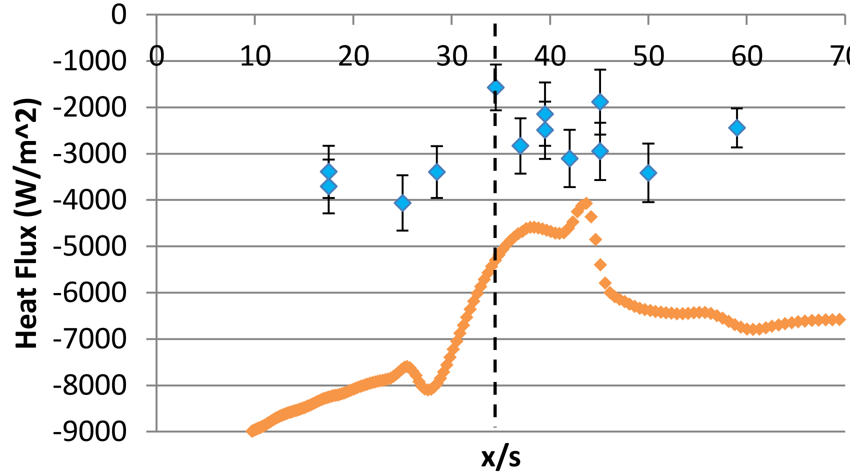
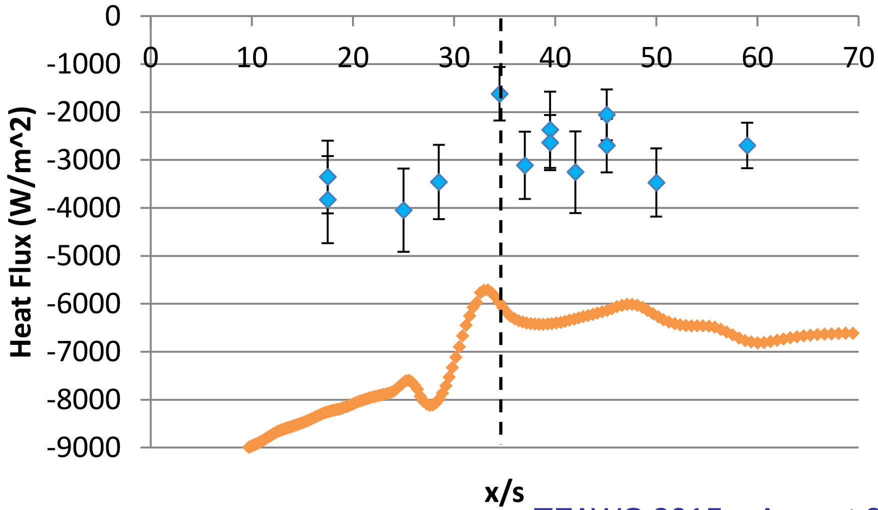
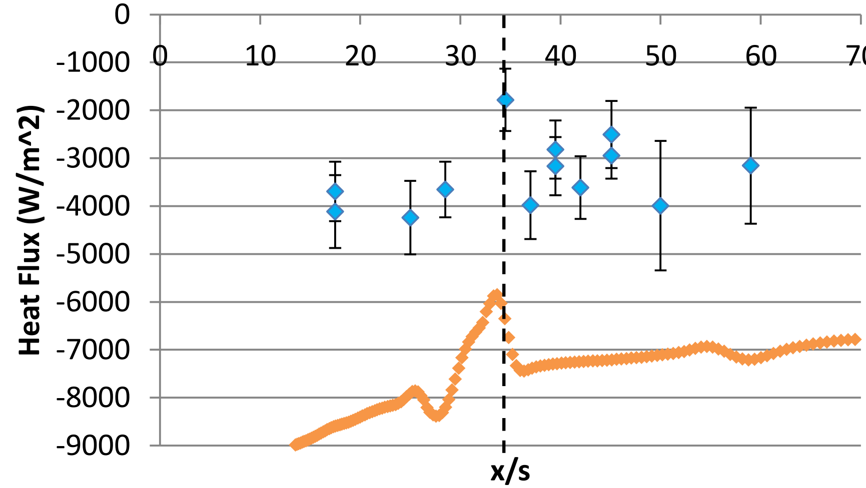


Case 2: Pressure Matched, M_{film} = 0.7



Case 3: Supersonic, M_{film} = 1.2



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Next Steps

- Improve our understanding of the discrepancy between experiments and simulations
- Improve our understanding of the heat flux instrument
  - Construct unit scale test blocks to measure heat flux gauge response to impulsive imposition of well known boundary conditions
  - Lead to better understanding of instrument error
- New measurements with favorable pressure gradient
  - More direct comparison to J-2X geometry and function
  - New test section is being designed now

Acknowledgements

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References

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